

An Evaluation of the Long Term Bridge Performance Program

Stephanie Fung
sfung09@gmail.com

Maricella Confessor
sweetmari07@yahoo.com

Theresa Lye
theresa_lye@hths.mcvsd.org

Miguel Rodriguez
el_lata91@hotmail.com

ABSTRACT

With the recent collapse of the I-35 bridge and the currently ineffective methods of bridge inspection, it is imperative that a new system of bridge data collection and inspection be developed. For these reasons, the Federal Highway Administration (FHWA) has initiated the Long Term Bridge Performance Program (LTBP), which is currently being developed at the Center For Advanced Infrastructure and Transportation (CAIT) at Rutgers. This program aims to obtain quantitative data using modern technology to monitor bridges. The LTBP team of the Governor's School at Rutgers experimented with ground penetrating radar technology and conducted an inspection of a bridge in Warren County, NJ using old, visual inspection techniques. The team aimed to discover how the LTBP program can be developed and how traditional methods of inspection compare to the proposed methods of inspection in the LTBP program. From these experiences, it was determined that the traditional methods of bridge inspection are subjective and inefficient, and that the more quantitative methods that will be implemented in the LTBP program would be more effective. While the LTBP program will also demand more time and financial support than the current system of bridge inspection, the team concluded that the improvement to the nation's bridge inspection system is necessary.

INTRODUCTION

The I-35 bridge, also known as bridge 9340, spanned the Mississippi River in Minneapolis, Minnesota, United States. The truss bridge carried about 140,000 vehicles daily with a capacity of about 159,000 pounds, and had been inspected every two years until 1993, after which it was inspected every year [4]. Investigations following the collapse indicated that the structural deficiencies responsible for the accident were located at the northern end of the bridge [5]. In particular, investigators believed the L-11 gusset plate, as well as the L-9 and U-10 connections were closely related with the failure. In addition, there

had been construction work on the bridge at the time, and investigators proposed that over weighting from the construction materials and equipment placed on the bridge were also responsible for the collapse.

There were various consequences that resulted from the failure of the I-35 bridge. While the loss of lives is a primary concern, the surrounding traffic systems were also complicated as the I-35 was a primary route in the Twin Cities' transportation network. Furthermore, the current reconstruction of the I-35 bridge forces funds to be diverted from other road repairs[6]. As such, the I-35 bridge exemplifies the necessity for a better system

of maintaining the condition of bridges and preventing further catastrophes similar to its collapse.

The systematic collection of data began when the Federal Highway Administration created the National Bridge Inspection Program, which stores the data from inspection reports in the National Bridge Inventory (NBI). Beginning in the 1980's, several state highway agencies conducted studies to improve their use of the NBI and develop systems of bridge inspection and data collection that could lead to an analysis of life-cycle costs. These studies, however, relied heavily on NBI data, which limited the effectiveness and novelty of these programs [2]. Realizing this shortcoming, certain states have created new bridge data collection systems such as AASHTOWare™ PONTIS, BRIDGIT, and OPBRIDGE Bridge Management Systems (BMSs) [1, 2]. They have also implemented "element level" condition assessments, which records data on the individual components of the bridge; the NBI system only collects information on a few general areas [2].

All of the systems previously described, however, do not support the detailed assessment of bridges needed for the implementation of life-cycle cost analyses and predictive models. Life-cycle cost analyses attempt to examine the performance of a bridge in relation to maintenance and other related costs, in an attempt to predict how those factors will be affected over time and, ultimately, to determine the efficiency of the structure. For such an analysis, reliable quantitative information on the deterioration, environment, maintenance, user safety, operational performance, and costs of the bridges is required. However, the NBI only contains qualitative data and is flawed because it holds information on only a few major components on the bridge such as the

deck, superstructure, and substructure [1]. Its rating system is subjective and vague and, due to the use of visual inspection techniques, may lack consistency.

Thus, current bridge databases can be deemed insufficient for life-cycle cost analyses and similar investigations. The implementation of such analyses, however, is imperative considering the current state of the highway bridges of the United States. The average age of over 600,000 bridges in the United States is forty-four years, and such a large number of aged bridges demands a systematic and effective program for bridge inspection and data collection. To remedy the issues associated with these old methods, the Long Term Bridge Performance Program (LTBP) was initiated.

In our project, the modern techniques, such as ground penetrating radar, were studied and tested locally. Although this innovative and new technology could not be taken on the full bridge inspection, they clearly demonstrated the potential of such a program, even when used in the parking lot on the campus of Rutgers University. For the full bridge inspection, traditional methods of visual evaluations were used and compared to previous reports. Both approaches yielded different results and varying conclusions could be drawn from each, but in the end, both proved that the Long Term Bridge Performance Program is essential for the structural integrity of our bridges.

The collapse of the I-35 bridge in Minnesota along with the lack of accuracy and consistency of outdated inspection systems has prompted the development of the Long Term Bridge Performance (LTBP) Program, which hopes to improve the quantitative inspection methods and use life-cycle cost analysis to expand our understanding of the economic efficiency of building and maintaining such bridges.

BACKGROUND

Under the leadership of Principal Investigator and Program Administrator Ali Maher, a team of engineers at the Rutgers Center For Advanced Infrastructure and Transportation (CAIT), was awarded a \$25.5 million contract by the Federal Highway Administration (FHWA) to develop the LTBP Program, a 20-year program that will inspect, analyze, and evaluate several bridges around the country. The LTBP Program will be developed with different phases. CAIT had begun working on the program since May 2008 and is planning to finish the try-out phase of the program by the end of 2009. [3] After that, depending on its success, it will continue gathering data until 2012, when results will be presented to the Congress to expand its funding until 2028.

The goal of the program is to gather quantitative data useful for the improvement of the current bridge construction methods and to decrease the amount of resources needed for the maintenance and reparation of all the bridges in the National Bridge Inventory. It aims to expand our current knowledge about bridges, how they deteriorate, how we design the bridges, how to improve life-cycle costs, and how to prepare our systems for the future bridge construction and data management. In addition, there is specific data that must be obtained in order for the program to maximize bridge performance and minimize the use of the amount of resources available. The program's data collection will include the damage and deterioration of the bridge and the operation and maintenance of the bridge [1]. Furthermore, as a result of the limited funding for this program authorized by the Congress in 2005 under the Safe,

Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) [3], decisions must be made about the type of data that will be collected. These decisions will be based on priority: how a particular component of the bridge affects the performance and deterioration. Also, the data will be affected by the necessity of certain bridges in the overall performance of a highway. Factors such as "traffic counts, truck weights, maintenance activities, geometry, etc." could be considered when determining the types of data that the LTBP should collect [1]. Also as a result of the limited funding, inspections will be carried out on only a few representative bridges. Furthermore, the LTBP Program plans to inspect these bridges utilizing current technology and methodologies; such as Ground Penetrating Radar (GPR), impact echo (IE), and Nondestructive Tests (NDT); to produce quantitative data to be stored in the database.

Testing

Inspections will be carried out on only a few representative bridges to reduce the number of bridges that must be examined due to economic restraints. Utilizing the NBI and other bridge databases, the bridge samples will be chosen to exhibit a wide variety of characteristics found in the majority of the bridges in the nation. A statistically representative sample will maximize the financial resources while providing a good cross-section of the bridge population. In addition, these bridges will fall into 3 categories: Periodically Inspected Bridges, which will be inspected regularly with visual inspection and NDT/NDE techniques, Instrumented Bridges, which will be examined continuously with sensing technology to measure the bridge's structural performance, and Decommissioned Bridges, which will undergo forensic autopsies to examine the

effects of corrosion, deterioration, overloads, and other causes for failure [1,9]. Once a representative sample of bridges has been obtained, several different techniques will be used to analyze the safety and performance of each bridge, such as the hammer tap or chain drag, which were employed even before the implementation of the Long Term Bridge Performance

Program. These old techniques included a variety of visual evaluations to assign numerical values to qualitative observations. However, these evaluations were oftentimes subjective and inaccurate, for they were based solely on the inspector's perspective. However, to improve that system, inspectors are required to complete an evaluation of the bridge, rating various components on a scale

Code	NBI Superstructure Condition Description
N	Not Applicable: Use for culverts.
9	Excellent Condition: Superstructure is in new condition (recently constructed).
8	Very Good Condition: Superstructure has superficial deterioration.
7	Good Condition: Superstructure has minor (isolated) deterioration. <ul style="list-style-type: none"> • Steel: minor corrosion, little or no section loss. • Concrete: minor scaling or non-structural cracking (isolated delamination or spalling). • Timber: minor weathering or splitting (no decay or crushing). • Masonry: minor weathering or cracking (joints have little or no deterioration).
6	Satisfactory Condition: Superstructure has minor to moderate deterioration. Members may be slightly bent or misaligned - connections may have minor distress. <ul style="list-style-type: none"> • Steel: moderate corrosion (section loss or fatigue cracks in non-critical areas). • Concrete: moderate scaling or non-structural cracking (minor delamination or spalling). • Timber: moderate weathering or splitting (minor decay or crushing). • Masonry: moderate weathering or cracking (joints may have minor deterioration).
5	Fair Condition: Superstructure has moderate deterioration. Members may be bent, bowed, or misaligned. Bolts, rivets, or connectors may be loose or missing, but connections remain intact. <ul style="list-style-type: none"> • Steel: extensive corrosion (initial section loss in critical stress areas). Fatigue cracks (if present) have been arrested or are not likely to propagate into critical stress areas. • Concrete: extensive scaling or cracking (structural cracks may be present), moderate spalling or delamination (reinforcement may have some section loss). • Timber: extensive weathering or splitting (moderate decay or crushing). • Masonry: extensive weathering or cracking (joints may have slight separation or offset).
4	Poor Condition: Superstructure has advanced deterioration. Members may be significantly bent or misaligned. Connection failure may be imminent. Bearings may be severely restricted. <ul style="list-style-type: none"> • Steel: significant section loss in critical stress areas. Un-arrested fatigue cracks exist that may likely propagate into critical stress areas. • Concrete: advanced scaling, cracking, or spalling (significant structural cracks may be present - exposed reinforcement may have significant section loss). • Timber: advanced splitting (extensive decay or significant crushing). • Masonry: advanced weathering or cracking (joints may have separation or offset).
3	Serious Condition: Superstructure has severe deterioration - immediate repairs or structural evaluation may be required. Members may be severely bent or misaligned - connections or bearings may have failed. <ul style="list-style-type: none"> • Steel: severe section loss or fatigue cracks in critical stress areas. • Concrete: severe structural cracking or spalling. • Timber: severe splitting, decay, or crushing. • Masonry: severe cracking, offset or misalignment.
2	Critical Condition: Superstructure has critical deterioration - primary structural elements may have failed (severed, detached or critically misaligned). Immediate repairs may be required to prevent collapse or closure. The load-carrying capacity may be severely reduced.
1	"Imminent" Failure Condition: Bridge is closed - superstructure is no longer stable (corrective action might return the structure to restricted service).
0	Failed Condition - Bridge is closed - superstructure is beyond the point of corrective action.

Table 1.0

of 0 to 9, with a score of 0 being “obsolete”

In addition to visual evaluations, aural inspection techniques were also utilized. For instance, a hammer was used to tap the concrete, and the varying pitches of the echoes that resulted were indicators of the condition of the pavement below the surface of the deck. A higher pitched echo meant that spalling was occurring underneath the surface of the deck, while a lower pitched echo signified a solid foundation underneath. Another aural technique that takes advantage of similar echo sounds is called the chain drag. In this method, a metal chain is dragged across the surface of the bridge while the inspector listens for changes in the pitch of the echo to signify the condition of the pavement below.

While these techniques have been the primary methods for inspecting bridges, they have been deemed insufficient for assessing bridge safety, and therefore, one of the aims of the Long Term Bridge Performance Program is the application of newer, quantitative methods to supplement the old. Impact echo and Ground Penetrating Radar (GPR) are both Non-Destructive Evaluation methods used to inspect bridges for the Long Term Bridge Performance Program.

The impact echo method is a nondestructive testing technique based on monitoring the surface of motion to detect flaws in the concrete. This method uses a device based on transient stress waves. These waves propagate through concrete and are reflected by internal flaws and external surfaces. It can be used to determine the location and extent of flaws such as delaminations, cracks, post-tensioned concrete structure. The practical application of stress wave methods for flaw detection in concrete has been to use

and a score of 9 being “new.

mechanical impact to generate the stress pulse. The impact produces a high-energy pulse that can penetrate deep into concrete to determine cracks and other internal defects. To generate a short pulse of ultrasonic stress waves, an electro-mechanical transducer is used to propagate into any object that is being inspected. The pulse is then reflected back to the transducer, which acts as a receiver. The signal received on an oscilloscope, the round trip travel time of the pulse sent, is calculate and the speed and distance of the reflecting can be determined [9].

The ground penetrating radar is used for the evaluation of pavement layer thickness to find deteriorations in the pavement. It is also used to find anomalies in the pavement after bridge construction. Some of these anomalies result from failures on the bridge deck. Most of the damage that a bridge receives is due to fatigue, or the damage that occurs in a material for cycling load [14]. GPR is able to detect these damages before any other method used for bridge inspection. This instrument can also be used to find cavities, foundation and other structures under pavements. As a result of its reliance on radar pulses instead of sound waves, GPR is more effective than the hammer tap and the chain drag methods at finding small changes in the bridge’s pavement.

Ground penetrating radar works by sending radar pulses to the ground and detecting the pulses that return. Reflections are produced when the pulse encounters a material with a different dielectric constant, which is “the ratio of the amount of stored electrical energy when a potential is applied, relative to the permittivity of a vacuum” [15]. Different materials have different

dielectric constants; therefore when the pulse hits a different material, part of the radar pulse is reflected back as a result of the change in the dielectric constant. The change in the dielectric constant is essential for the accurate inspection of bridges.

Dielectric Constant: Air = 1 Asphalt = 3-5
Concrete = 6-8

After the pulse is reflected, a receiver, next to the antenna that produces the pulses, detects the pulse and calculates the distance at which the change in dielectric constant occurred. The distance is calculated by measuring the time it took the pulse to go and come back. The speed of the radar pulse is equal to the speed of light or 299,792,458 meters per second [16]. The GPR could also be used to detect and calculate the thickness of the different layers. This helps to detect the changes and movements of the concrete in the bridges.

The GPR system goes through eight phases to send, receive and display the data:

1. A trigger pulse is generated in the control unit at a normal repetition rate of about 50 KHz, with a receiving time of 20 microseconds.
2. The trigger pulse is sent through the control cable to the transmitter electronics in the transducer (antenna).
3. In the transducer, each trigger pulse is transformed into a bipolar pulse with a higher amplitude than the trigger pulse. The pulse shape varies with the electronics and the antenna.
4. The transmit pulse then propagates along the antenna and is radiated into the subsurface. The size of the antenna and electrical properties of the subsurface determine the

frequency of the propagating energy (larger antenna = lower frequency).

5. In the subsurface, reflections occur at boundaries where there is a dielectric contrast. The reflected portion of the signal travels back to the antenna.
6. The receiver in the antenna detects the returning signal and sends it back to the control unit.
7. In the control unit the signal is processed and displayed.
8. The output of the graphic recorder or the display on the video is a representation of the analog signal.
 - The horizontal axis is distance along the surface.
 - The vertical axis is two-way travel time of the radar pulse in nanoseconds.
 - The signal amplitude determines the shade of grey on the paper or the color on the video display.

The GPR is affected by two electrical properties, the already discussed dielectric constant, and the electrical conductivity. This is the ability of a material to conduct electricity. Conductivity has a big impact in the radar performance. The higher the electrical conductivity, the harder it is for the radar pulse to penetrate the ground. Therefore, materials like air, dry granite, dry limestone, concrete and asphalt have good radar conditions because they are considered low conductivity materials. In contrast, materials like wet clay, wet shale seawater, ice, snow give poor radar readings because of their high electrical conductivity.

Ground penetrating radar is one of the most sophisticated and most efficient ways of conducting Non-destructive Testing

on bridges. Its sensitive radar pulse helps inspectors find problems earlier than with any other type of method. As a result, repairs can be done sooner and more severe damage that could cause the collapse of a structure can be prevented. With the creation of new software and computers, the use of Ground penetrating radar is easier and gives more detailed information than with the old computers. When using a computer software to read the signals from the GPR, the inspector can see the different changes underneath the concrete of the bridge's deck. The software displays the information in different ways. Color displays are useful to find difference between the layers, gray scale displays more information, and the oscilloscope trace is easier than read than any of the other. Therefore, technology is used to fit the type of data that should be collected.

METHODS

Prior to the full bridge inspection, a demonstration of the ground penetrating radar was performed in the parking lot outside of the Center for Advanced Infrastructure and Transportation. The GPR system was attached to the back of a van, and as the van was driven around the parking lot, a laptop screen inside of the van displayed the readings that were picked up from the radar. Although this system could not be used on the full bridge inspection, it provided key insight into the potential of this new technology.

As part of our research, a first hand inspection to a bridge in Warren County, NJ was conducted. A laptop with the Advitam BDS system software was used to conduct and record the inspection. This software had all of the different elements of the bridge preset and in the order in which these elements should be inspected. The database uses a rating score from 0 to 9; nine

meaning excellent condition and zero meaning functionally obsolete. The computer already had the numbers and the information with the description of each of the rating numbers, making the rating even easier for the inspectors. This inspection must be conducted from top to bottom to avoid inaccuracies. Besides the laptop to record information, a camera was also used to record evidence to support our inspection. The pictures taken were automatically added to the report by the laptop. A small hammer and a ruler were also used to record measurements. The hammer was used to tap different parts of the bridge and the sounds that were emitted could be used to draw conclusions about the deck underneath the surface. After we gathered all of the necessary data, we moved to the report phase of the inspection. Taking advantage of the new technology that the software possesses, the report was written automatically and instantaneously by the software. (See Appendix A).

RESULTS

As the ground penetrating radar passed over the asphalt in the parking lot, varying shades of grey bands were observed on the laptop screen. These bands represented the layers of varying dielectric constants of the ground beneath the surface. As the GPR passed over a concrete slab covering some metal piping, the disturbances were observed on the laptop screen as well.

From the inspection of bridge 2102005 of Warren County, the team assigned the structure a General Recommendation rating of 7. Overall, the bridge was in good condition and was neither structurally deficient nor structurally obsolete.

Abutments & Wingwalls

The bearing, anchor bolts, and pads were assigned a rating of 8. The elements were in

good condition and did not display signs of significant deterioration. The backwall was assigned a rating of 7, while the erosion and scour of the beginning and end abutments were assigned ratings of 6 and 7 respectively. For the wingwalls, the walls were assigned a rating of 6, while the erosion and scour of both abutments were assigned ratings of 7.

Approaches

The embankment, which exhibited stable soil and foliage and did not display signs of erosion, was assigned a rating of 8, while the settlement was assigned a rating of 7. On the northeast and southeast corners of the bridge, a settlement of 2.5 inches was apparent between the approach and bridge deck. Also, the pavement was assigned a rating of 6. It contained spalled and cracked areas, although these deteriorated areas had undergone minor repairs. The guide railing was in good condition and was assigned a rating of 8. The railing did not exhibit any dents, breaks, or deteriorated portions.



Figure 1.0

Superstructure and Deck Elements

The wearing surface and deck structural were assigned a rating of 7. The surface of the deck exhibited only a few small, minor cracks and overall did not display any significant signs of deterioration and damage. The curbs, sidewalks, and fascias were in worse condition and were assigned a rating of 5. The concrete of these elements exhibited corrosion and spalling in several areas. A relatively significant case of spalling was located on a northern curb and was 30 inches long, 6 inches high, and 3 inches deep. (see Figure 1.0) In addition, there was a settlement of about 3 inches between the curb and the bridge deck. The members and joints of the bridge were observed to be in good condition and did not exhibit significant signs of deterioration or damage and thus were assigned a rating of 7. Additionally, the paint was given a rating of 8, as it appeared to be in almost new condition, with no indicators of peeling, cracking, discoloration, or corrosion.



DISCUSSION/CONCLUSION

Although the bridge was over twenty years old, most of the elements of the bridge

received a rating of 7 or higher, meaning that overall, the bridge was in very good condition. There were some minor faults,

such as some settling of the sidewalks and small cracks in the concrete, but the majority of the bridge was in almost new condition, including aspects such as the paint and joint condition. Most faults were only aesthetically imperfect, not structurally compromising, and therefore were considered only minor, or secondary, priorities.

One reason for the “very good” condition of this bridge despite its age could be the limited traffic and load that it must carry. This bridge spanned only 130 feet across a small stream, and the forces and loads that it must endure cannot be compared to those of a suspension bridge spanning a large river between two cities. From this, it can be concluded that although this bridge received excellent ratings, other aspects, such as location and frequency of use, should be considered when choosing bridges to evaluate for the Long Term Bridge Performance Program. Bridges such as these are among the most common in the United States, but individually, they are not as significant as some of the larger bridges.

During the inspection itself, members of the inspection committee sometimes found it difficult to agree on a rating for certain elements. Because a basis of comparison did not exist, one’s opinion of a rating of 7 may be different from that of their inspection counterpart. The severity of some problems may also be weighed differently depending on the judgments of the inspectors, and some problems may even be overlooked by chance.

The differences in opinion during the inspection demonstrate the subjectivity of the traditional inspection methods and the large margin of error that they allow. While huge discrepancies are rare, even minor inconsistencies from year to year can lead to inefficiency, compromising bridge safety

and precious economic resources. With the new technology of the Long Term Bridge Performance Program, these assessments can be supplemented with more dependable data.

As mentioned before, the most prevalent methods used to check for spalling beneath the deck utilized aural techniques. In this inspection, the hammer tap method was used to detect changes in pitch, a phenomenon that results from changes in concrete composition beneath the surface. The changes in pitch were noticeable, especially in the specific areas that were tested. However, it would be impractical to test the entire bridge deck, and therefore, an accurate “display” of the entire surface could not be obtained.

The aural methods of testing for spalling are effective if the inspector knows where to test. However, to obtain a more comprehensive analysis of the bridge deck below the surface, technology such as the ground penetrating radar or impact echo system can be utilized, a key aspect of the Long Term Bridge Performance Program.

One key part of the traditional inspection process is the ease of use. The computer software that is currently being used does not require a deep understanding of the bridge inspection processes, and therefore, there would be limited training needed for future inspectors. The new technology, however, involves more complex machinery that would require more intensive training. The new systems are also much more expensive than the visual inspections that are used currently, and therefore would require companies to invest more money into the safety of their bridges, a choice that some may not choose to make.

There are several negative components to the modernization of the bridge inspection system, and though the

conventional methods are satisfactory, the safety of the transportation systems in the United States is worth more than the additional monetary and time investment that must be put in to improve our nation's infrastructure.

FUTURE WORK

Because the Long Term Bridge Performance Program is a newly established organization, there are several developments that could promote the future success of this program. Currently there are only two ground penetrating radar systems in the nation, a fact that is limiting the expansion of such a useful tool. In order for such technology to become ubiquitous in the bridge inspection field, it must become more readily available.

The ground penetrating radar could not be used on the bridge that was inspected for this report due to unavailability, but the use of the GPR in the future could detect any damage to the bridge deck below the surface. Small cracks were observed on the surface of the deck, and these cracks could be an indication of something more serious down below.

Due to natural barriers such as the stream and excessive brush, some parts of the bridge were inaccessible by foot. With the use of ladders and more protective clothing, it would be possible to inspect all parts of the bridge, rather than making unsupported assumptions. This would make for a more accurate and useful inspection report. This problem may not necessarily apply to all other bridges, especially the larger bridges that span longer distances and require more drastic measures. For these instances, it may be more reasonable to assume than to compromise the safety of the inspectors.

The first expansion mentioned will undoubtedly come with the growth of the program, and with time, such problems will be irrelevant. The latter, however, depends greatly on the location of the bridges that are constructed, and therefore will be an everlasting and universal obstacle.

ACKNOWLEDGEMENTS

We would like to thank the following people for their continual time and support throughout the research project. We express our utmost gratitude to Andrew Foden and the Long Term Bridge Performance team at Rutgers for guiding and educating us on bridge inspection concepts, as well as for planning and leading our group on a hands-on bridge inspection in Warren County. The information they taught us contributed greatly to our experience and to the writing of this paper. In addition, we would like to thank our project counselor Titi Omodunni Osunfisan, who helped us tremendously throughout the project and the creation of this paper. Finally, we would like to thank all who made the Governor's School of Engineering and Technology possible, in particular program coordinator Blase Ur, who provided guidance and advice during the progress of this project.

REFERENCES

1. Chase, Steve and Hamid Ghasemi. "Implications of the Long Term Bridge Performance Program for Life Cycle Costing."
2. Hooks, John M. "Evolution of Bridge Performance Data and Assessments."
3. "Rutgers Research Team Awarded Federal Highway Administration Bridge Performance Program Contract Worth up to \$25.5 Million." Rutgers Focus. 23 Apr 2008. Rutgers .
<<http://news.rutgers.edu/medrel/news->

releases/2008/04/rutgers-research-tea-20080422>.

4. "I-35W bridge fact sheet." Minnesota Public Radio. 3 Aug 2007.
<http://minnesota.publicradio.org/display/web/2007/08/03/bridge_background/?rssource=1>.

5. Stachura, Sea. "Northern end of I-35W bridge is now focus of probe." Minnesota Public Radio. 5 Aug 2007. 17 Jul 2008
<<http://minnesota.publicradio.org/display/web/2007/08/05/ntsb/>>.

6. Scheck, Tom. "I-35W bridge reconstruction could delay other projects." Minnesota Public Radio. 5 Aug 2007.

7. "I-35 Bridge Collapse, Minneapolis, MN." U.S. Department of Transportation. Office of Public Affairs. 17 Jul 2008
<<http://www.dot.gov/affairs/factsheet080207.htm>>.

8. Wald, Matthew L.. "Deficient, but Not Necessarily Dangerous ." The New York Times. 5 Aug 2007.
<http://www.nytimes.com/2007/08/05/weekinreview/05basicB.html?_r=2&oref=slogin&oref=slogin>.

9. Carino, Nicholas J.. "The Impact-Echo Method: An Overview." BFRL: Fire on the Web. National Institute of Standards and Technology.
<<http://www.fire.nist.gov/bfrlpubs/build01/PDF/b01005.pdf>>.

10. Ghasemi, Hamid. "The FHWA Long-Term Bridge Performance Program." AASHTO: The Voice of Transportation. Federal Highway Administration.
<<http://www.transportation.org/sites/bridges/docs/Long%20Term%20Bridge%20Performance.pdf>>.

11. Venderzee, Peter J. . "FHWA's Long Term Bridge Performance program has the makings of a champion." Roads & Bridges. November 2007.
<http://www.roadsbridges.com/popup_app/index.cfm?fuseaction=showArticle&appDirectory=rb&articleID=8689&forPrint=yes>.

12. "Long-Term Bridge Performance Program ." Turner-Fairbank Highway Research Center. 25 Apr 2008 . Federal Highway Administration.
<<http://www.tfhr.gov/structur/ltp.htm>>.

13. Deaver, Rick, Abdul-Hamid Zureick and Brian Summers. "Repairs with High-Performance Materials Make Bridges Stronger, Last Longer." Tech Transfer. University of California Berkeley.
<<http://www.techtransfer.berkeley.edu/newsletter/03-3/carbonfiber.php>>.

14. "Fatigue (material)." Wikipedia: The Free Encyclopedia. 17 Jul 2008
<[http://en.wikipedia.org/wiki/Fatigue_\(material\)](http://en.wikipedia.org/wiki/Fatigue_(material))>.

15. "Relative static permittivity." Wikipedia: The Free Encyclopedia.
<http://en.wikipedia.org/wiki/Dielectric_constant>.

16. "Radar." Wikipedia: The Free Encyclopedia.
<<http://en.wikipedia.org/wiki/Radar>>.

